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Rotary Kiln Incineration: The Effect of Oxygen Enrichment on Formation of Transient Puffs during Batch Introduction of Hazardous Wastes

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Research Triangle Park, NC

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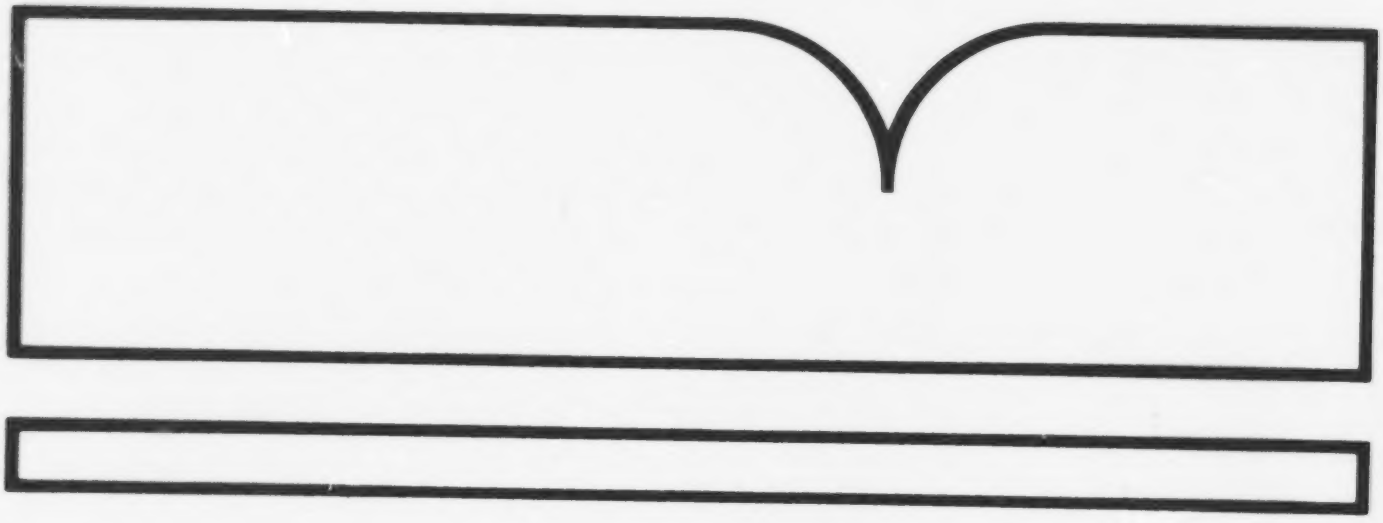

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ROTARY KILN INCINERATION: THE EFFECT OF OXYGEN ENRICHMENT ON FORMATION OF TRANSIENT PUFFS DURING BATCH INTRODUCTION OF HAZARDOUS WASTES

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16. ABSTRACT The paper discusses results of experiments on a 73 kW (250,000 Btu/hr) rotary kiln incinerator simulator equipped with a prototype oxygen enrichment burner, to determine the effect of oxygen enrichment on the magnitude and intensity of transient puffs emitted during batch introduction of contained liquid surrogate waste (toluene) on corncob sorbent. Results show that the effect of oxygen enrichment at constant temperature is to decrease the size of the transient puff, but that increases in kiln temperature associated with oxygen enrichment can offset this and cause net increases in the transient emissions. This effect is likely due to increases in the rate of waste volatilization. These results were especially true for particulate matter and are consistent with previous results without oxygen enrichment.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Incinerators		
Oxygen	Liquid Waste	07B
Wastes	Hazardous Waste	14G
Toxicity	Puffs	06T
Toluene	Transient Emissions	

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INTRODUCTION

Oxygen enrichment has long been applied to many industrial combustion processes in order to increase product yields and thermal efficiency. The use of oxygen in hazardous waste incineration to augment or enrich oxidant levels in the combustion zones has the potential to improve the destruction and removal efficiencies (DREs) of the principal organic hazardous constituents (POHCs), minimize the formation of products of incomplete combustion (PICs), and allow for better control of the combustion process.

The use of oxygen enrichment in rotary kiln incinerators is of interest as a potential method of minimizing transient failure conditions caused by the batch introduction of waste material. Rotary kiln incinerators are unique in that they are designed to allow a portion of their waste load to be charged in batch rather than continuous mode. In this batch mode of operation, solid wastes and "containerized" liquid wastes are introduced through entrance chutes, typically cocurrent with the gas flow. Kiln angle and rotation speed continuously expose fresh surface for oxidation, determine the residence times of non-combustible materials, and provide for continuous ash removal. Upon entry into the incinerator, the liquid waste container, typically cardboard, plastic, or steel drums, ruptures or burns, exposing the contents to the hot kiln environment. The liquid then rapidly vaporizes and reacts with the excess oxygen present in the combustion gases from the continuous primary flame. A possible kiln failure condition arises when the evolution of waste gases from the ruptured container is more rapid than the rate at which the stoichiometric amount of oxygen can be supplied from the primary flame. This transient overcharging condition, unique to batch mode systems, can lead to a "puff" of incompletely destroyed organic material which must subsequently be destroyed by the system afterburner. Under circumstances when the afterburner cannot destroy the quantity of organic material produced, this puff leads to a system failure.

This paper discusses results of part of an in-house program at the U.S. Environmental Protection Agency (EPA) directed toward gaining engineering insight into potential problem areas related to rotary kiln incineration. General objectives are to delineate fundamental combustion phenomena that are important in the generation of transient puffs from batch fed wastes. It is not within the scope of this work to do exhaustive POHC, PIC, or DRE analyses. The specific objectives of the work presented here are to determine the effects of oxygen enrichment through the primary flame on the formation of transient puffs, caused by the batch introduction of a contained surrogate liquid waste (toluene) on sorbent into a rotary kiln incinerator simulator. Further, the tests and analysis techniques attempt to separate the individual effects of dilution, temperature, oxygen flow, and oxygen partial pressure. Results from tests utilizing this simulator to examine transient puffs from prototype solid plastic wastes and contained surrogate liquid wastes without oxygen enrichment have been presented previously.[1,2]

This paper is divided into four sections. Following the Introduction, the Experimental Approach is discussed. Next, Results and Discussion of the experimental study are presented. Finally, the findings from this study are summarized in the Conclusions.

EXPERIMENTAL APPROACH

The EPA rotary kiln incinerator simulator has been described in detail previously,[1,2] and therefore, is not presented again here. It has been established that the simulator, although sized at only 73 kW (250,000 Btu/hr), exhibits the salient features of full-scale units with thermal ratings 20 to 40 times larger. The simulator matches the volumetric heat release, gas-phase residence time, and temperature profile of many full-scale units, and yet is flexible enough to allow parametric testing. A schematic drawing of the simulator is presented in Figure 1.

The water-cooled prototype burner is designed to produce stable flames utilizing oxidant streams ranging from 22 to 100 percent oxygen. The burner provides for separate introduction of natural gas, air, and oxygen with turndown ratios of at least 1 to 10. The burner is easily ignited and capable of rapid response to changes in the fuel, air, or oxygen flows. Liquid oxygen was provided in cryogenic Dewar tanks, with each tank containing approximately 127 m^3 (4500 scf) of gaseous oxygen.

Contained batch charges to the rotary kiln are introduced through a sliding gate/ram assembly located downstream of the continuous natural-gas-fired oxygen-enriched main burner as shown in Figure 1. Quantification of the transient puff produced requires the real-time measurement of system response variables. These dependent variables include peak responses of O_2, CO, CO_2, NO_x, and total volatile hydrocarbon concentrations (THC) measured by continuous

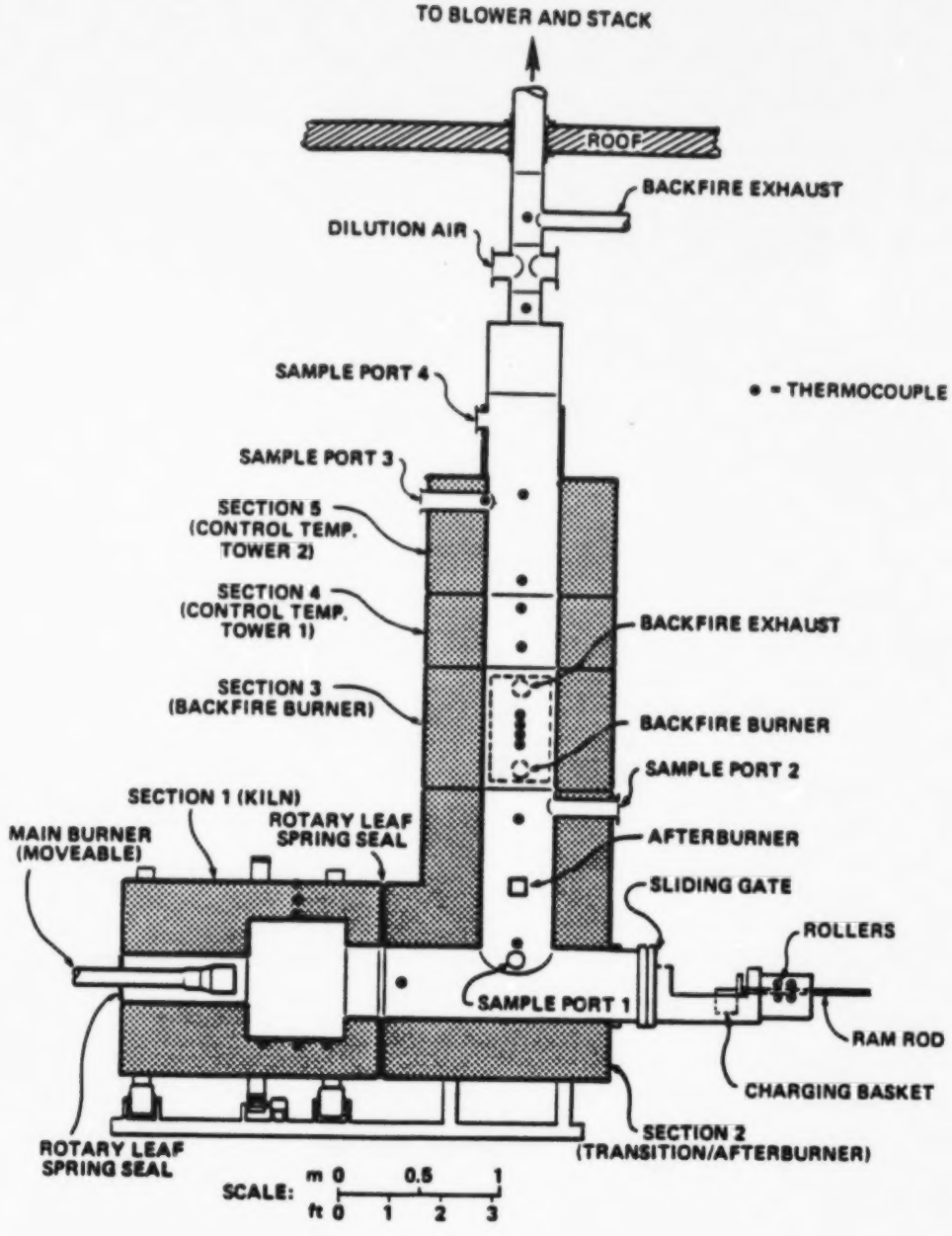


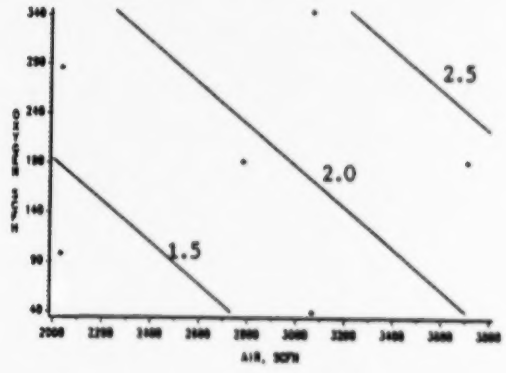
Figure 1. EPA incinerator simulator, cutaway view.

flame ionization detection (FID) and reported in equivalent parts per million (ppm) methane. Other dependent variables include the time-integrated responses of the THC analyzer and particulate filter weight. At constant sampling conditions, these variables are proportional to the total mass emitted in the transient puff. Weighed desiccated quartz filters and the heated particulate filter system upstream of the THC analyzer were used to collect particulate samples. Volatile hydrocarbons are defined as those in the gas-phase at 420 K (300 °F), the temperature of the heated sample line.

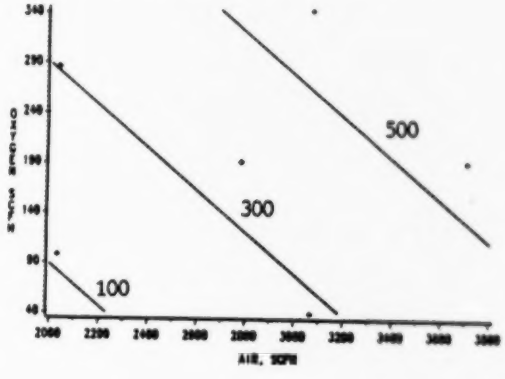
Charges to the kiln were kept constant for all tests presented in this paper. Only the natural gas, air, and oxygen flows to the prototype burner were varied by test design to cause changes in the oxygen flow, partial pressure, and stoichiometric ratio. Charges to the kiln consisted of 100 g (0.22 lb) of toluene on 135 g (0.30 lb) of ground corncob sorbent sealed in a 45 g (0.10 lb) cylindrical uncoated 1 qt (0.95 l) cardboard container. Similar charges were used in previous work by this group.[2] Toluene was chosen because it yields large chlorine-free puffs to which the FID is very sensitive. Toluene also produces large particulate loadings. A charge mass of 100 g (0.22 lb) was chosen because it provides large puffs which did not greatly exceed the FID linear response region of zero to 10,000 ppm (reported as methane) for the conditions tested.

As with the previous studies, a portion of the experimental design was based on response surface experimentation.[3] This methodology allows, on the basis of one experiment involving a minimal number of trials, determination of an empirical relationship between the response and the controlled variables in the experimental region. For the first set of experiments, the flows of oxygen and air were chosen as the controlled or independent variables. The natural gas auxiliary fuel feed rate (kiln load) was held constant. These variables are of intrinsic interest to an incinerator operator because they are directly controlled. By defining these flow rates to the burner, several other system parameters are defined. These calculated variables include; stoichiometric ratio, primary flame oxygen enrichment, total flow (approximately inversely proportional to residence time), primary flame oxygen and nitrogen flows, adiabatic flame temperature, post primary flame oxygen flow, and post primary flame oxygen partial pressure. Throughout this first set of experiments, the natural gas flow was held constant at 5.66 m^3/hr (200 scfh), and the oxygen and air flows to the burner were varied by experimental design to examine six combinations (plus one duplicate) of oxygen and air flows. Figure 2 presents the combinations of air (57.5 to 105.0 m^3/hr, 2030 to 3707 scfh) and oxygen (1.13 to 9.74 m^3/hr, 40 to 344 scfh) flows that form the second order rotatable pentagonal design (data points denoted by +). Figure 2 also shows that these air and oxygen flows correspond to a range of calculated stoichiometric ratios from 1.3 to 2.4 (Figure 2a), post flame oxygen flows from 3.29 to 16.37 m^3/hr (116 to 578 scfh) (Figure 2b), and post primary flame oxygen partial pressures from 5.0 to 16.0 percent

(a) STOICHIOMETRIC RATIO



(b) POST FLAME OXYGEN FLOW,SCFH



(c) POST FLAME OXYGEN PARTIAL PRESSURE,%

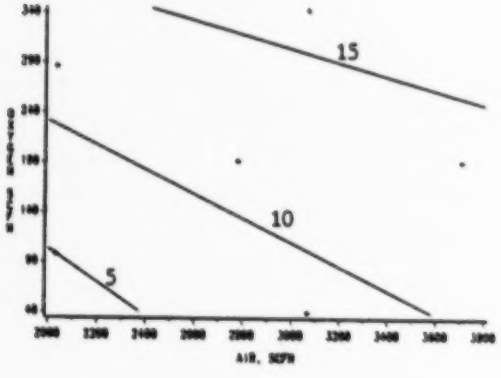


Figure 2. Contours of constant (a) stoichiometric ratio, (b) post flame oxygen flow, and (c) post flame oxygen partial pressure over the test region examined by data set 1 (response surface experiments). Trial matrix points denoted by +.

(Figure 2c). A summary of the final trial matrix including the controlled and derived system variables is presented in Table I.

The seven (six plus one duplicate) experiments, described in Figure 2 and Table I, were conducted in the following manner. The desired natural gas, air, and oxygen flows were set, and the kiln was allowed to thermally equilibrate to the new condition for at least 5 hours. Charges were prepared, sealed, and introduced to the kiln at approximately 10 minute intervals. Between 10 and 12 replicate charges were recorded and averaged for subsequent statistical analysis. Kiln rotation speed, kiln pressure, and burner position were kept constant at 0.5 rpm, -37.4 Pa (-0.15 in. H_2O), and -0.34 m (-13.5 in.) inside the kiln front wall, respectively. Note that the effect of the kiln alone is being examined. There was neither afterburning nor external heating of the combustion products. We are trying to determine the behavior of the kiln and, subsequently, the relative role of the afterburner to ensure adequate destruction.

Based on the results of the first set of response surface experiments, a second and third series of two dimensional tests were performed in an attempt to separate the individual effects of stoichiometric ratio, post flame oxygen flow, and post flame oxygen partial pressure. The design of the response surface experiments was limited. It is evident from Figure 2 that, for the response surface experiments, the three oxygen parameters (stoichiometric ratio, post flame oxygen flow, and post flame oxygen partial pressure) are highly correlated with each other and vary in the same manner. In fact, due to the constant auxiliary fuel load used for these experiments, specification of either stoichiometric ratio or post flame oxygen flow defines the other. To separate these effects, two sets of additional experiments were designed, varying the auxiliary fuel load. These trial matrices are presented in Tables II and III. The trial matrix in Table II, was designed to vary the post flame oxygen flow and partial pressure independently while holding stoichiometric ratio constant. The trial matrix in Table III, varies stoichiometric ratio and post flame oxygen partial pressure while holding post flame oxygen flow constant. The individual data sets were collected in the same manner as described previously for the response surface experiments, and other kiln operating parameters were held constant as described above. It was hoped that the additional experiments might indicate whether post flame oxygen flow or post flame oxygen partial pressure had the greater influence on transient puffs. While the post flame oxygen flow (total molar oxygen flow to which the waste charge is exposed) may be varied without oxygen enrichment, variation of the post flame oxygen partial pressure is limited without oxygen enrichment.

RESULTS AND DISCUSSION

Results are presented in two parts. First, the measured puff is considered without correction for any dilution effects. This repre-

Table I. Trial matrix for data set 1 (response surface experiments, constant gas flow).

Test	Gas flow, scfh	Air flow, scfh	Oxygen flow, scfh	Total flow, scfh	Oxygen enrichment, percent	Total oxygen flow, scfh	Nitrogen flow, scfh
1	200	3707	192	4099	24.8	967	2932
2	200	3066	40	3306	21.9	681	2425
3	200	2030	98	2328	24.5	522	1606
4	200	2030	286	2516	30.7	710	1606
5	200	3066	344	3610	28.9	985	2425
6	200	2780	192	3172	26.0	773	2199
7	200	2780	192	3172	26.0	773	2199

Test	SR*	Post flame oxygen flow, scfh (FO_2)	Post flame oxygen partial pressure, percent (PO_2)	Adiabatic flame temp, K	Measured kiln exit temp, K
1	2.4	560	13.7	1454	1125
2	1.7	274	8.3	1687	1172
3	1.3	116	5.0	2125	1201
4	1.7	304	12.1	2017	1200
5	2.4	578	16.0	1584	1151
6	1.9	367	11.6	1732	1181
7	1.9	367	11.6	1732	1159

*stoichiometric ratio

Table II. Trial matrix for data set 2 (two dimensional experiments, constant stoichiometric ratio).

Test	Gas flow, scfh	Air flow, scfh	Oxygen flow, scfh	Total flow, scfh	Oxygen enrichment, percent	Total oxygen flow, scfh	Nitrogen flow, scfh
8	150	2732	40	2922	22.0	611	2161
9	150	1249	350	1749	38.2	611	988
10	200	3707	40	3947	21.7	815	2932
11	200	2224	350	2774	31.7	815	1759
12(20)	250	4679	40	4969	21.6	1018	3701
13(21)	250	3196	350	3796	28.7	1018	2528
14	300	5656	40	5996	21.5	1222	4474
15	300	4173	350	4823	27.0	1222	3301

Test	SR*	Post flame oxygen flow, scfh (FO_2)	Post flame oxygen partial pressure, percent (PO_2)	Adiabatic flame temp, K	Measured kiln exit temp, K
8	2.0	306	10.5	1508	1000
9	2.0	306	17.5	2107	1047
10	2.0	408	10.3	1494	1112
11	2.0	408	14.7	1891	1190
12(20)	2.0	510	10.3	1487	1213
13(21)	2.0	510	13.4	1782	1286
14	2.0	613	10.2	1482	1247
15	2.0	613	12.7	1716	1320

*stoichiometric ratio

Table III. Trial matrix for data set 3 (two dimensional experiments, constant post flame oxygen flow).

Test	Gas flow, scfh	Air flow, scfh	Oxygen flow, scfh	Total flow, scfh	Oxygen enrichment, percent	Total oxygen flow, scfh	Nitrogen flow, scfh
16	150	3708	40	3898	21.7	815	2933
17	150	2225	350	2725	31.7	815	1760
18	200	4194	40	4434	21.6	917	3317
19	200	2711	350	3261	29.9	917	2155
20(12)	250	4679	40	4969	21.6	1018	3701
21(13)	250	3196	350	3796	28.7	1018	2528
22	300	5165	40	5505	21.5	1119	4086
23	300	3682	350	4332	27.8	1119	2912

Test	SR*	Post flame oxygen flow, scfh (FO_2)	Post flame oxygen partial pressure, percent (PO_2)	Adiabatic flame temp, K	Measured kiln exit temp, K
16	2.7	510	13.1	1239	931
17	2.7	510	18.7	1575	1011
18	2.2	510	11.5	1380	1071
19	2.2	510	15.6	1693	1151
20(12)	2.0	510	10.3	1487	1213
21(13)	2.0	510	13.4	1782	1286
22	1.8	510	9.3	1571	1255
23	1.8	510	11.8	1844	1340

*stoichiometric ratio

sents what must be handled by the afterburner and is of interest to operators and designers of rotary kiln systems. Next, two sets of data are presented that have been corrected for dilution effects. These represent the rates of volatile release from the waste.

Set 1: Dilution Effects Not Considered

Full quadratic models with respect to air and oxygen flows were fitted to the data from the first set of experiments (Table I) using weighted least squares, where the weights were equal to the number of replicates. These models, obtained using the preprogrammed procedures in SAS (Statistical Analysis System), should not be considered unique since other models might attain fits essentially identical to those reported here. Once determined, these models can be described pictorially through response surface plots. The response surface plots are unique to the data they describe. Figure 3 presents these contour plots for the dependent variables: volatile hydrocarbon peak area (peak area) (Figure 3a), volatile hydrocarbon peak concentration (peak height) (Figure 3b), carbonaceous particulate filter weight (filter weight) (Figure 3c), and CO peak concentration (peak CO) (Figure 3d) versus oxygen and air flows. Full quadratic models were able to explain total response variances (r^2) of 0.9485, 0.8992, 0.9993, and 0.9610 for peak area, peak height, filter weight, and peak CO, respectively. The variance is a measure of the dispersion of the response, defined as the square of the standard deviation. Evident from Figure 3 is that, for all the response variables, transient puffs are reduced at higher air and oxygen levels. Peak area and peak height responses at high air and oxygen flows (upper right corners) are approximately nine and five times less, respectively, than at low flows (lower left corners). Filter weight response decreases by a factor of four over the same region, and peak CO by a factor of six. It is important to note, however, that a portion (but not all) of these response reductions can be explained by simple dilution. Total flow changes by a factor of 1.8 over this experimental region, but due to the fact that we are trying to characterize the inlet conditions to which an afterburner system must be able to respond, we have not corrected these data for dilution.

The response curves in Figure 3 can be compared with the contours of constant stoichiometric ratio, post flame oxygen flow, and post flame oxygen partial pressure, presented in Figure 2. It is not surprising that puff intensities should be reduced at higher oxidant levels and higher total flows. In addition to the effect of dilution, providing higher oxygen flows and higher oxygen partial pressures to the vaporizing waste cause fuel rich regions to be more difficult to achieve. However, without oxygen enrichment, it is often difficult in practice to operate at high stoichiometric ratios while maintaining kiln temperatures and flame stability due to the quenching effect of nitrogen. Also evident from Figure 3 is the fact that all three responses are more sensitive to changes in oxygen flow than to changes in air flow. Small changes in oxygen flow cause large changes in stoichiometric ratio, post flame oxygen flow, and

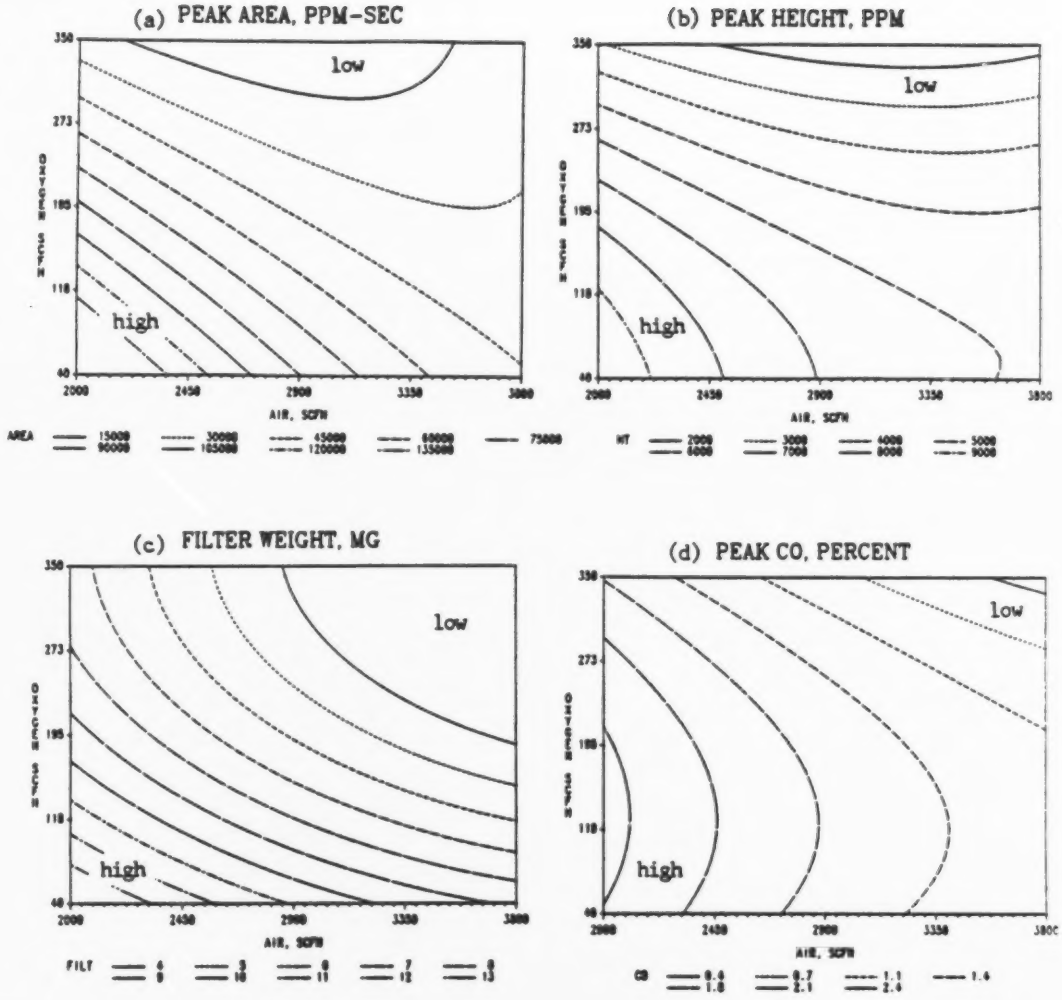


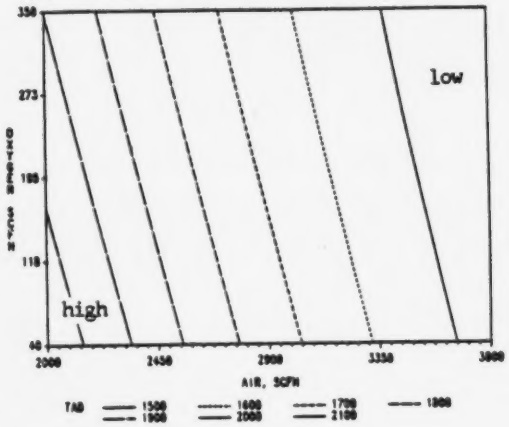
Figure 3. Data set 1 response surface contour plots for (a) volatile hydrocarbon peak area, (b) volatile hydrocarbon peak height, (c) particulate filter weight, and (d) peak CO. Data are not corrected for dilution.

post flame oxygen partial pressure, without significantly affecting the adiabatic flame temperature or gas-phase residence time. Conversely, large changes in air flow are necessary to effect changes in stoichiometric ratio or post flame oxygen flow. Without oxygen enrichment, oxygen partial pressure is limited by atmospheric conditions. Additionally, increasing air flow also significantly decreases the adiabatic flame temperature, flame stability, and gas-phase residence time.

The response curves of Figure 3, however, do not describe the individual effects of the derived system variables. It is important to establish the individual effects of stoichiometric ratio, oxygen enrichment, residence time, adiabatic flame temperature, measured kiln temperature, post flame oxygen flow, and post flame oxygen partial pressure on the response variables. It has been shown previously[1,2] that, with respect to transient puffs from batch waste introduction, increasing kiln temperature increases puff intensity and that this is likely due to increased vaporization rates. This result is in contrast to typical kiln operating practice under steady-state operation, where increased temperatures are desirable because they increase the kinetic rates of oxidation reactions. Thus, for batch waste, while oxygen enrichment may increase the flame stability, flame stoichiometry, post flame oxygen flow, and post flame oxygen partial pressure, increased temperatures may drive the waste into the gas-phase more rapidly. We must try to quantify the relative magnitudes of each of these mechanisms. Figure 4 presents the calculated adiabatic flame temperatures and total flow rates through the rotary kiln simulator over the range of air and oxygen flow rates investigated by the first set of experiments (Table I). System residence time is roughly proportional to the inverse of the total flow. Comparison of Figure 4 with the response curves in Figure 3 shows that the regions of lowest peak area, peak height, filter weight, and peak CO responses correspond to the regions of low adiabatic flame temperature and high total flow (low residence time). The effect of high total flow can be explained by simple dilution. Additionally, the effect of increased temperature with respect to transient puffs is counterintuitive to normal steady-state incineration practice but consistent with increased vaporization rates.

To determine the relative importance of each of these controlled, measured, and derived variables on the response variables, single term linear models were constructed from the data of the first set of experiments (Table I). Table IV presents the response variance explained for each independent variable examined individually. The results show that the three derived variables of most significance in explaining the variance in the response variables are post flame oxygen flow, stoichiometric ratio, and post flame oxygen partial pressure. As previously mentioned, the experimental design was such that all three of these variables are highly correlated and indicate the oxygen available to the vaporizing waste. Of lesser importance are the variables: total oxygen flow, residence time, adiabatic flame temperature, total flow, primary flame oxygen enrich-

(a) ADIABATIC FLAME TEMPERATURE, K



(b) TOTAL FLOW, SCFH

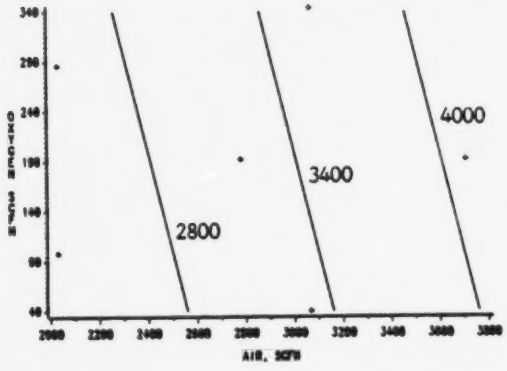


Figure 4. Contours of constant (a) adiabatic flame temperature and (b) total flow over the region examined by data set 1 (response surface experiments). Trial matrix points denoted by +.

Table IV. Fraction of variance (r^2) of data set 1 explained by single term linear models.

Variable	Peak area ppm-sec CH_4	Peak height ppm CH_4	Filter weight mg	Peak CO ppm
Post flame oxygen flow, scfh (FO_2)	0.8494	0.8389	0.9460	0.8618
SR*	0.8510	0.8395	0.9467	0.8636
Post flame oxygen partial pressure, percent (PO_2)	0.9359	0.8632	0.9374	0.7887
Total oxygen flow, scfh	0.7633	0.8170	0.5519	0.5078
Residence time, 1/scfh	0.5199	0.6204	0.6903	0.7284
Adiabatic flame temperature, K	0.5148	0.6267	0.6938	0.7317
Total flow, scfh	0.4380	0.6089	0.6596	0.6920
Oxygen enrichment, percent	0.4759	0.5917	0.1894	0.2094
Measured kiln exit temperature, K	0.3293	0.4614	0.5935	0.5258
Air flow, scfh	0.2382	0.4513	0.5114	0.5423

*stoichiometric ratio

ment, measured kiln temperature, and total air flow. These results indicate that, for the experimental region examined here, transient puffs can be reduced by providing increased oxygen to the waste, and that even though increasing the oxygen flow may change the temperature and residence time, the effects of increased available oxygen dominate. It is important to note that these data indicate only a secondary effect due to temperature, even though previous results[1,2] indicated that temperature has a major effect on the intensity of transient puffs from batch incineration. Calculated adiabatic flame temperatures for this experimental set vary from 1450 to 2000 K (2150 to 3140 °F), yielding an experimental range of 550 K (990 °F). In actuality, however, the measured kiln exit temperature varies only from 1125 to 1200 K (1565 to 1700 °F); therefore, this actual experimental range of 75 K (135 °F) may be insufficient to establish any temperature effects.

Figures 5 and 6 present the single term linear models for post flame oxygen flow and post flame oxygen partial pressure, respectively, versus peak area (Figures 5a and 6a), peak height (Figures 5b and 6b), filter weight (Figures 5c and 6c), and peak CO (Figures 5d and 6d). Again, due to the experimental design of the first data set, similar plots for stoichiometric ratio are identical to those for post flame oxygen flow. Figures 5 and 6 include the averaged data for each of the seven experimental conditions (denoted by +), as well as the 95 percent confidence regions around each linear model. All the data indicate decreasing response with increasing post flame oxygen flow (and stoichiometric ratio) and post flame oxygen partial pressure. Attempts were made to add additional linear and quadratic terms to the models; however, these additions did not significantly increase the variance explained. Again, note that a portion of these responses can be explained by simple dilution.

A possible disadvantage to oxygen enrichment for use in hazardous waste incineration is the potential to produce high concentrations of nitrogen oxides (NO_x) due to the increased temperatures and increased available oxygen. Effects of the latter may greatly exacerbate this problem if high nitrogen containing wastes are incinerated, although even if the waste contains little or no nitrogen, thermal fixation of ambient nitrogen may produce unacceptable quantities of NO_x. Figure 7 presents contours of baseline nitric oxide (NO) concentration over the region examined by the first experimental set (Table I). The data are presented as measured (Figure 7a) and corrected to 7 percent oxygen (Figure 7b) in the exhaust gas. Concentrations as high as 1500 ppm (at 7 percent oxygen) were determined for high oxygen operating conditions using natural gas auxiliary fuel only.

Sets 2 and 3: Corrected for Dilution Effects

As stated previously, the second and third data sets (Tables II and III) were intended to separate the individual effects of stoichiometric ratio, post flame oxygen flow, and post flame oxygen partial

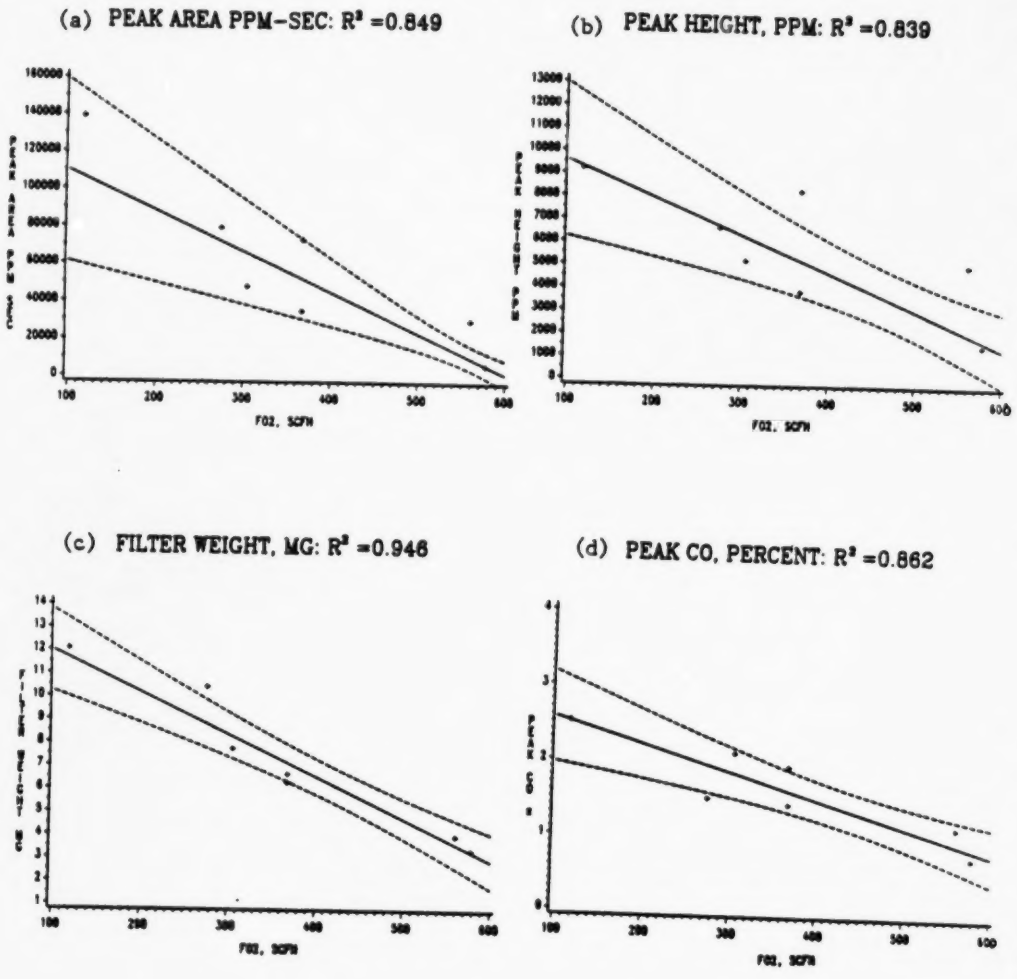


Figure 5. Single term linear models describing response of (a) volatile hydrocarbon peak area, (b) volatile hydrocarbon peak height, (c) particulate filter weight, and (d) peak CO versus post flame oxygen flow (FO_2). Averaged data from data set 1 (response surface experiments) denoted by +. Solid lines indicate best linear fit; dotted lines indicate 95 percent confidence region. Data are not corrected for dilution.

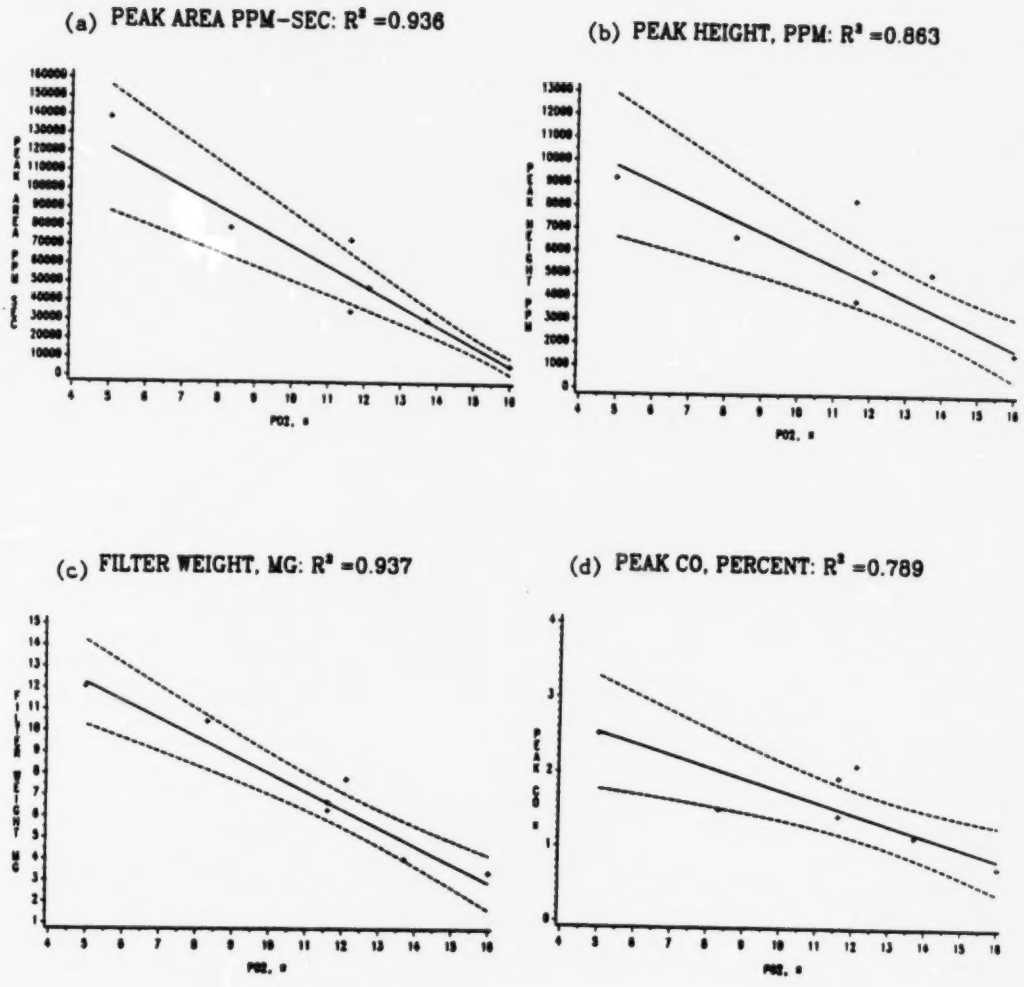


Figure 6. Single term linear models describing response of (a) volatile hydrocarbon peak area, (b) volatile hydrocarbon peak height, (c) particulate filter weight, and (d) peak CO versus post flame oxygen partial pressure (PO_2). Averaged data from data set 1 (response surface experiments) denoted by +. Solid lines indicate best linear fit; dotted lines indicate 95 percent confidence region. Data are not corrected for dilution.

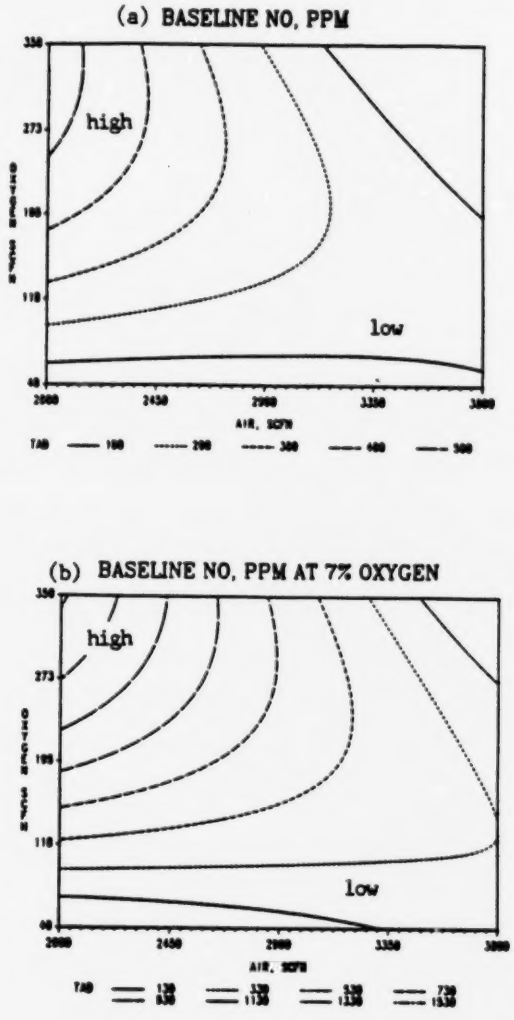


Figure 7. Contours of constant baseline NO flue gas concentration (a) as measured and (b) corrected to seven percent oxygen over the region examined by data set 1 (response surface experiments).

pressure. By varying the natural gas load to the kiln, experiments were designed in which these three parameters vary independently. The purpose was to determine the relative importance of the molar flow rate of oxygen to the waste charge (proportional to post flame oxygen flow) and the volumetric oxygen concentration available to the waste charge (equal to the post flame oxygen partial pressure). Two-dimensional plots of post flame oxygen flow and post flame oxygen partial pressure versus the response variables were prepared at constant stoichiometric ratio (SR=2.0). Additionally, similar plots of stoichiometric ratio and post flame oxygen partial pressure versus the response variables were prepared at constant post flame oxygen flow (FO_2=14.4 m^3/hr, 510 scfh). These data were all corrected for dilution by normalization to a standard total flow of 113 m^3/hr (4000 scfh). These plots showed the data to be scattered, and no consistent trend existed between all of the response variables. A likely explanation for these inconsistent results is that, in addition to the effects of changes in the post flame oxygen flow and partial pressure, confounding influences due to large changes in kiln temperature are included. By changing the kiln load, necessary to effect changes in post flame oxygen flow and partial pressure, measured kiln exit temperatures vary over a wide range (320 K, 576 °F). It has been shown previously[1,2] that the effect of increased kiln temperature is increased transient emissions and that this is likely due to increased volatility. Data have also shown that for toluene, a known soot precursor, soot formation is disproportionately promoted over volatile hydrocarbon emissions with increasing temperature.[2] Due to the confounding influences of temperature, no conclusions can be drawn that separate the individual effects of post flame oxygen flow and partial pressure. However, overall, the effect of oxygen enrichment via the primary combustion chamber to minimize the emissions from transient puffs does not seem to be dramatic over the experimental region examined here. Indeed, it can be detrimental when the effects of temperature are included.

To illustrate that the effect of increasing kiln temperature can be detrimental to transient emissions, Figure 8 presents filter weight data from each of the second and third experiment sets (Tables II and III) versus measured kiln exit temperature. Data from experiments taken at constant stoichiometric ratio (SR=2.0) (Figure 8a) and constant post flame oxygen flow (FO_2=14.4 m^3/hr, 510 scfh) (Figure 8b) are presented. These data, relating to low oxygen flow/enrichment (open symbols) and high oxygen flow/enrichment (solid symbols), have been corrected for dilution by normalization to a standard total flow of 113 m^3/hr (4000 scfh). Data taken at similar kiln loads are connected. The data show fair correlation between filter weight and measured kiln exit temperature, and indicate a trend of increasing particulate emissions with increasing temperature over the experimental range examined here. The data may indicate some slight reduction in particulate emissions due to oxygen enrichment at similar kiln loads, as shown by the dotted lines on Figure 8. However, if the oxygen enrichment causes a dramatic increase in the kiln temperature, particulate emissions are actually increased. This is also

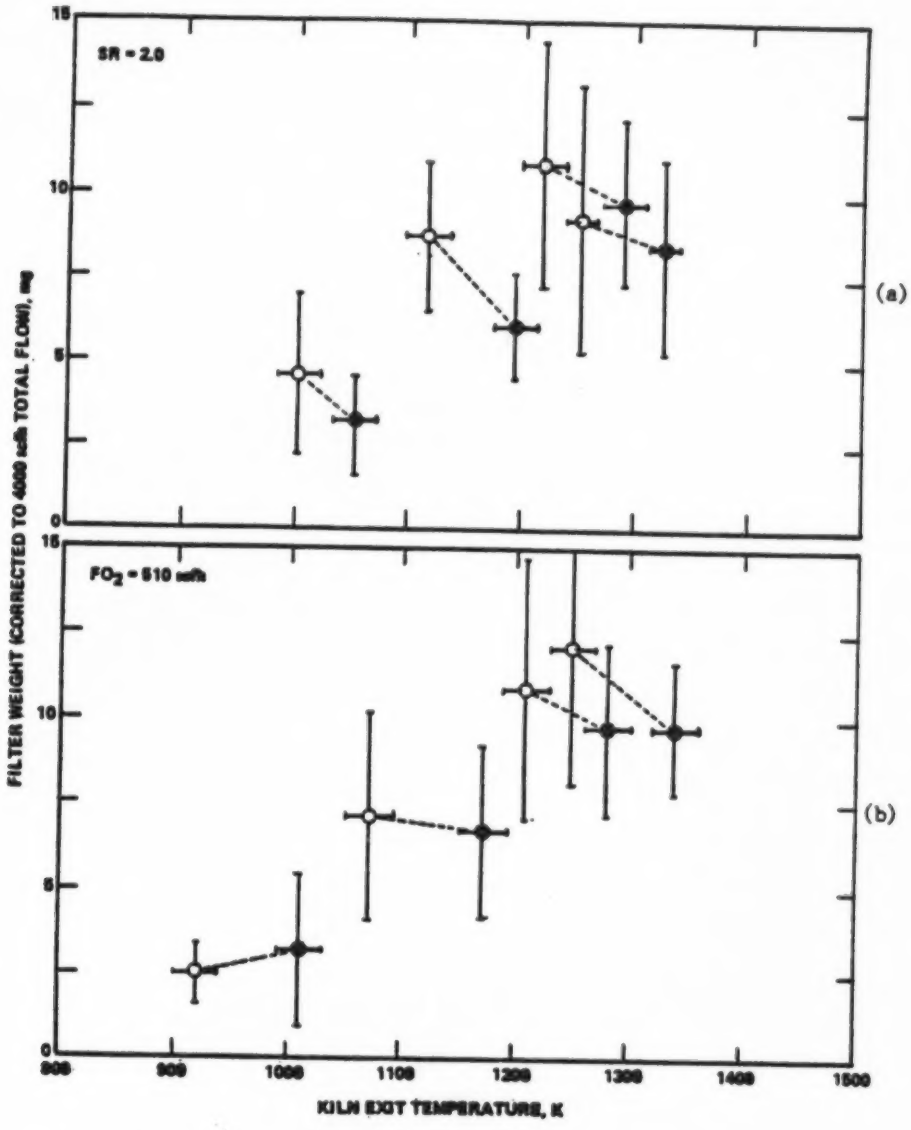


Figure 8. Results from data sets 2 and 3 (two dimensional experiments) showing the relationship between filter weight and measured kiln exit temperature for (a) constant stoichiometric ratio (SR) and (b) constant post flame oxygen flow (FO_2). Data are corrected to 4000 scfh total flow. Open symbols indicate tests at low oxygen flow/enrichment (1.13 m^3/hr, 40 scfh). Solid symbols indicate tests at high oxygen flow/enrichment (9.91 m^3/hr, 350 scfh). Tests at similar kiln load (natural gas flow) are connected.

illustrated in Figure 8 by comparison of all open or solid symbols.

CONCLUSIONS

The results of experiments involving the use of oxygen enrichment via the primary flame (primary combustion chamber) of a rotary kiln incinerator simulator feeding batch charges of contained liquid surrogate waste (toluene) on corncob sorbent are consistent with results previously presented by the authors.[1,2] A summary of the results from this study includes:

1. The phenomena associated with transient puff formation from the batch introduction of contained waste are fundamentally different from those associated with steady-state incineration. The realization of these differences is important in order to minimize organic emissions.
2. Although increased temperatures associated with oxygen enrichment may provide potential benefits for steady-state incineration, these increased temperatures are detrimental in controlling transient puffs from contained wastes. This was especially true for particulate emissions.
3. It is difficult to draw conclusions regarding the individual effects of stoichiometric ratio, or post flame oxygen flow, or post flame oxygen partial pressure due to the confounding effects of temperature.
4. When the effects of temperature are removed, oxygen enrichment causes a reduction, beyond simple dilution, in the magnitude and intensity of transient puffs from contained wastes.
5. If temperature increases can be controlled (e.g. by using advanced forms of process control), oxygen enrichment may cause net decreases in transient puff emissions. Results of planned tests on such a system at EPA's Combustion Research Facility in Arkansas may provide these answers.
6. Oxygen enrichment may cause unacceptable emissions of nitrogen oxides (NO_x) even at baseline conditions burning clean auxiliary fuel due to thermal fixation of ambient nitrogen. These emissions may be exacerbated if high nitrogen containing wastes are incinerated.
7. The data indicate that the rotary kiln serves primarily to pyrolize the waste into the gas-phase, and that complete oxidation is not likely in the primary chamber even with the help of oxygen enrichment. It may be desirable to operate the kiln at reduced temperatures in order to retard the rate of volatile release of waste species from the solid or liquid phase, and rely on the afterburner for complete organic destruction.
8. Efficient design and operation of afterburner systems for these incinerators are crucial in order to minimize organic emissions, especially with regard to transient emissions.
9. Oxygen enriched burners may be more useful when utilized as part of an afterburner system where increases in temperature are desired and do not cause increases in the rate of solid or contained liquid waste volatilization.

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DISCLAIMER

The research described in this article has been reviewed by the Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. The contents of this article should not be construed to represent Agency policy nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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